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# Microarcsecond scintillation-induced variability (MASIV) survey of the northern sky

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We present the results of a large-scale 5-GHz Very Large Array (VLA) survey of the northern sky searching for sources that exhibit intraday variability (IDV). The observations were made over four epochs, each of 3 days in January, May and September 2002 and January 2003. The objective is to obtain a large sample of IDV sources in order to derive reliable statistics of the microarcsecond properties of the source population and the scattering properties of the interstellar medium.

*Keywords*: IDV; Interstellar medium; VLA survey

## 1. Introduction

There is now considerable evidence to establish interstellar scintillation (ISS) in the turbulent, ionized interstellar medium (ISM) of our Galaxy as the principal mechanism responsible for intraday variability (IDV) seen in many flat-spectrum Active galactic nuclei (AGN) [1, 2]. A source must be small to scintillate; in the weak scattering case at frequencies of $\geq$5 GHz, the source angular size must be comparable to or smaller than the angular size of the first Fresnel zone, which implies microarcsecond angular sizes for screen distances of tens to

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hundreds of parsecs. The long time-scale over which scintillations have been observed in some sources suggests that such scintillating components are relatively long-lived despite their small physical sizes. ISS probes AGN angular sizes and brightness temperatures at centimetre wavelengths that are unachievable with Very Long Baseline Interferometry (VLBI).

## 2. The microarcsecond scintillation-induced variability survey

We undertook a large-scale 5-GHz VLA survey of a core sample of 525 compact, flat-spectrum AGN over the northern sky (declination $>0°$) to search for IDV [3]. Our objective was to obtain a statistically significant sample of sources exhibiting IDV in order to address a number of important astrophysical questions.

The sources were chosen from the JVAS [4–6] and CLASS [7] catalogues. Spectral indices were determined from the 8.5-GHz flux densities and the 1.4-GHz NVSS catalogue, and a flat-spectrum sample selected to have spectral indices greater than $-0.3$. We chose different weak and strong source samples, approximately 250 sources each. The weak sample consisted of sources with 8.5 GHz catalogued flux densities between 105 and 130 mJy, whereas the strong sample contained sources with flux densities more than 600 mJy. Sources were selected to cover the northern sky with individual source measurements being made every 2 h, with 60 s on-source per scan. This gave $\sim$6 scans per source per day, or $\sim$10,000 scans per epoch. Primary flux density calibration was based on observations with each sub-array of B 1328+307 (3C286) and J2355+4950; the latter is a compact gigahertz-peaked-spectrum source which is monitored at the VLA as part of their regular calibrator-monitoring program.

The VLA was sub-divided into five sub-arrays of five or six antennas each, so as to minimise slew times and hence maximise observing times. The source list was subdivided into four declination bands and one sub-array assigned to each. The fifth sub-array was used for more intensive monitoring of selected sources known to show IDV. The observations were undertaken during VLA reconfiguration times. The observations took place over four 72-h periods during January, May and September 2002 (96 h) and January 2003. This was done to ensure that our survey sampled each source over the course of the year so that sources that were in the 'slow' part of their annual cycle would not be missed. As a follow-up, we undertook a fifth 3-day epoch of observations in January 2006.

## 3. Objectives

Our objective was to produce a sample of at least 100–150 scintillators. Previous IDV surveys of the stronger flat-spectrum sources had found roughly 15% of the sources exhibited IDV; we started with a core sample of 525 sources, the maximum number that we could observe once every 2 h sampled with the four sub-arrays. With such a large sample size and number of scintillators, we can expect to explore possible dependencies in the presence or absence of microarcsecond angular structure in AGN on a variety of parameters.

A further objective was to survey a weak sample to compare the incidence of IDV in both weak and strong sources. The inverse Compton limit suggests that ISS may be more common among the weaker sources since for a given angular size the brightness temperature decreases with decreasing flux density.

We also hoped to find more of the very rapid scintillators such as PKS 0405–385 [9], J1819+3845 [10] and PKS 1257–326 [1]. As two of these three remarkable sources were discovered serendipitously, we hoped to find more such sources and to ascertain how common

they were and if they were more likely among the weaker or stronger sources. Moreover, as such rapid scintillation is due to scattering by nearby turbulent, ionized clouds, the presence of new fast scintillators would signify the presence of nearby, turbulent clouds.

Only with a large sample of scintillators is it feasible to explore the dependence of scintillation on parameters such as sky distribution and hence to explore the structure of the turbulent ISM. Again a large sample size allows us to search for any redshift dependence which might signify the presence of turbulent, ionized material in the intergalactic medium (IGM).

Microarcsecond angular resolution at centimetre wavelengths is not achievable with Earth-based VLBI space observatory programme as such long baselines are not part of the VSOP Space VLBI mission [11] and so ISS remains the only way to achieve such high angular resolution and to explore AGN structure and evolution at the highest brightness temperatures at centimetre-wavelengths.

## 4. Classification of variables

The uncertainties in the individual measurements are made up of two components: a fractional error, $p\%$, due to pointing uncertainties, and a noise error, $s$ Jy, due to thermal noise and confusion. For this study, $p = 1\%$ and $s = 1.5$ mJy. As a first step, sources were classified as variable if their modulation index, defined as the rms of the 3 days' observations divided by the mean flux density, exceeded twice that calculated from the above errors. On direct inspection of the data, however, it soon became apparent that many of the slower variables, *i.e.* sources with variability time-scales longer than 3 days, were not being noted as variable with the simple two-sigma cut described above. We then tried a similar two-sigma selection, but this time based on the daily averages rather than the individual measurements. This process yielded more variable detections, but again inspection revealed that there remained many sources exhibiting variability that were still not being detected.

The difficulty is that Chi-squared test is not an ordered statistic; therefore, low-level, monotonic variability that is easily detected on inspection was not being detected with this test. We were left with no alternative but to undertake 'by eye' inspection and classification. This was done independently by two of us. We adopted the conservative null hypothesis that 'each source was considered non-variable unless otherwise demonstrated'. The number of 'disagreements' was small. Any source where there was disagreement on its classification was reviewed, and if we could not agree on the classification, was classified non-variable; most sources where we initially disagreed were classified as non-variable.

Figure 1 shows some examples of the variability uncovered in the microarcsecond scintillation-induced variability (MASIV) survey. J1819+3845 [10] was found to be by far the most dynamic variable with a modulation index of 17%, even though our 2-hourly sampling was, at times, less than the variability time scale. Variability was very clearly detected on each of the four epochs. J0949+5819 demonstrates the sensitivity of our VLA measurements even in our five-sub-array mode.

The removal of 43 sources that showed structure or confusion left us with a final sample of 482 sources. Figure 2 shows the observed numbers of sources classified as non-variable or as variable in 1, 2, 3 or 4 epochs. A total of 56 sources, 12%, were seen to vary on each of the four observing epochs.

However, with any analysis of such a large number of observations, false positives, *i.e.* sources that are incorrectly classified as variable, are a significant concern. We believe that our classification of the light curves as variable or is not reliable with 95% confidence level. The question is how many false positives, non-variables missclassified, are there and how are they distributed? Probability theory shows that we expect 81.5% of the non-variables to

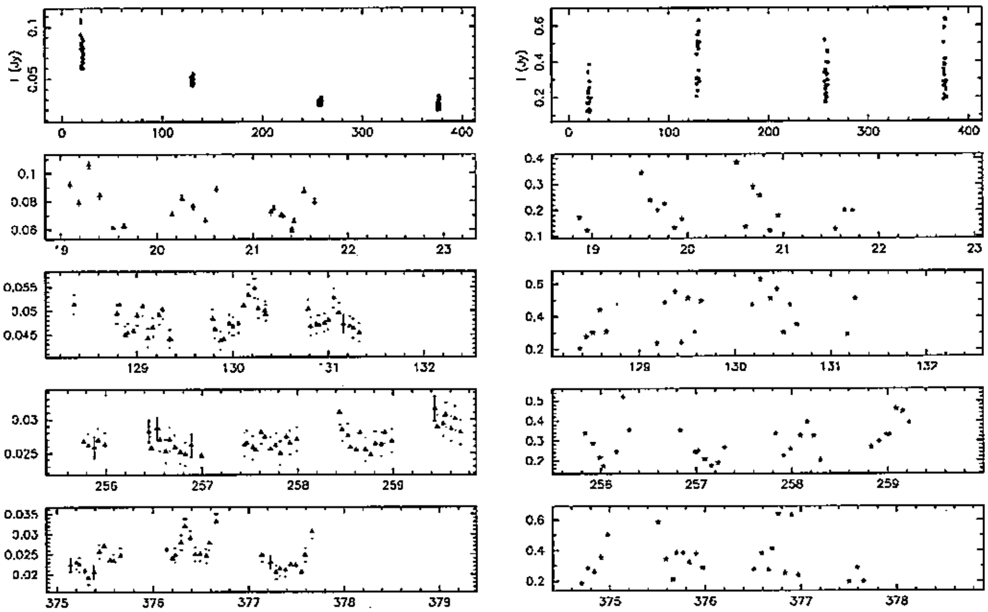

Figure 1. Examples of MASIV variability. J0949+5819 (left) and J1819+3845 (right). The top panel in each case shows all the total intensity data for the source against day number from 1 January 2001. The lower four panels show light curves for each of the first four epochs. The horizontal scale is the same (4 days) in each case.

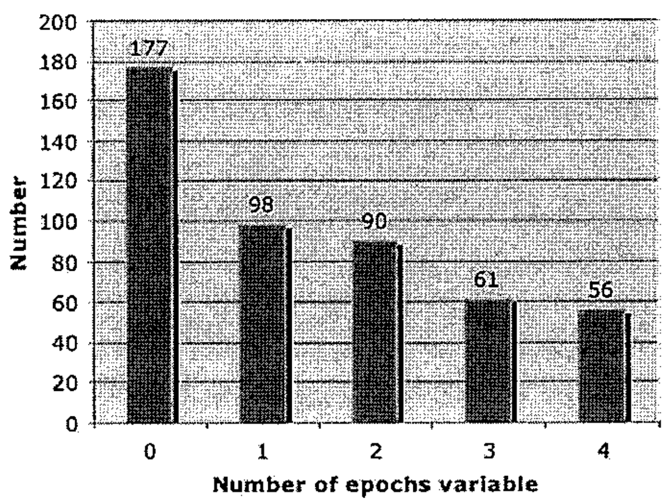


Figure 2. Variability statistics for the 482 sources surveyed. Sources are divided into the number of epochs they were seen to vary. Sources not seen to vary in any epoch were classified non-variable, *i.e.* variable in zero epochs.

be correctly classified. Of the remaining 18.5%, 17.1% are missclassified as variable on a single epoch, with a mere 1.4% as variable on two epochs. The large number of sources, 207, classified as variable on multiple epochs establishes that our classification is both reliable and accurate. Even if our classification was 90% reliable, the fraction of sources missclassified as variable on multiple epochs remains <5%.

This allows us to make a clear separation. We define those 177 sources that showed no variability in any of the four epochs as 'non-variable', and those 207 sources that showed

variability on two or more of the four epochs as 'variable'. With these definitions, we have two large and reliable samples each of approximately 200 sources, where non-variables act as a control sample for variables. Each was drawn from the same selection criteria and cover the same overall area of sky.

An important question remains to be answered, namely 'What fraction of the sources can be reliably classified as variable?' As noted above, the fraction of missclassified non-variables as one-time variables to correctly classified non-variables is 21%(17.1/18.1). It follows that the number of non-variables missclassified as one-time variables is 37, yielding a corrected total number of 268 variables. Therefore, the fraction of variables to non-variables is 56%, a value which is significantly higher than that found in any previous IDV survey!

## 5. Comparison of variables and non-variables

We have compared the fraction of strong and weak sources in our final sample of 482 sources. There are close to equal fractions of non-variables, one-time variables and 2+3+4 times variables in the strong (37%, 21% and 42%) and weak (37%, 19% and 44%) parts of our final sample. However, the two distributions differ in that the weak sources contain a significantly higher fraction of three-times and four-times variables than the strong sample sources. Lovell *et al.* [3] found that the number of sources with rms flux density variations greater than 4% of the mean flux density increases with decreasing flux density of the source. Our finding, an excess of the three-times and four-times variables, accounts well for this.

Those 61 sources now correctly classified as varying on only one of the four epochs form an interesting class of episodic variables, as they form almost 13% of the total. Thus, the microarcsecond components of AGN have life-times lasting from less than 4 months, the time between our observational epochs, to decades, the times over which some well-observed sources have continued to show ISS, B0917+624 [12,13], PKS 1519–273 [14], J1819+3845 [15] and PKS 1257–326 [2]. It is only because of our sampling over a full year that we find such short-lived, episodic scintillators.

A further surprise (at least to us) was the apparent absence of those very rapid variables. J1819+3845 fell in our sample, but it was the only source to show such variability. J0929+5013 showed rapid variability in the January 2002 epoch [3] but, although monitored closely, revealed only slower, many-hour variability in the three later epochs. We had expected to find more of these rapid variables especially given that two of the three known variables, J1819+3845 and PKS1257-326, were found serendipitously.

One possibility is that such variability is predominantly episodic, as is the case with PKS 0405–385 [16]. However, both PKS 1257–326 and J1819+3845 are long lived as both were still scintillating when last observed. For PKS 1257–326, the life-time is at least a decade [2] and at least half a decade for J1819+3845 ([15], and de Bruyn, private communication). For each of the three known fast variables, it is the nearby scattering screen that is responsible for the rapid variability. Thus, it would seem that such nearby screens cover very little of the sky.

## 6. Variability time scales

During the 'by eye' examination we noted the presence of any inflection points (*i.e.* change in sign of the derivative) at each epoch in order to derive an indication of the variability time scale of each source. The majority, 80%, was found to show none or at most one inflection point, implying variability time scales are $\geq$3 days; we have only underestimates of both the time scales and modulation indices for these. A further 13% showed two inflection points with

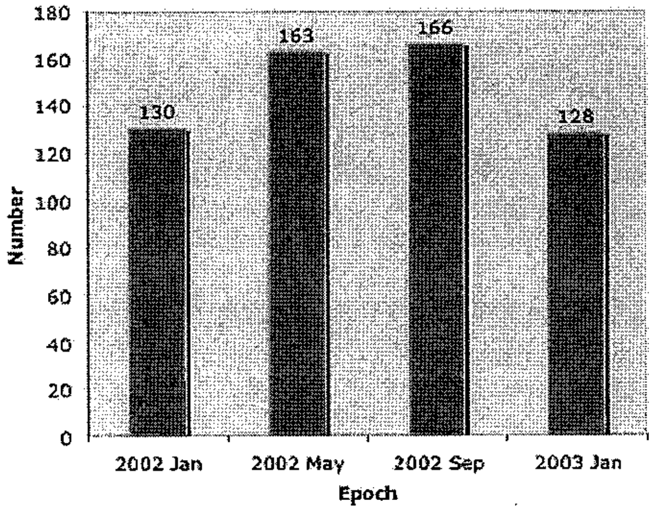


Figure 3. Numbers of sources classified as variable in each epoch. Screens moving at the local standard of rest would be expected to result in fewer variables beeing seen in epoch 3; we see no such deficit.

only 7% showing three or more. Overall, the distribution of time scales was statistically the same for each epoch, remembering that epoch 3 was 4 days rather than 3 days for the other epochs. A comparison of the distribution of inflection points for the weak and strong sources revealed no significant difference between the two classes.

The annual cycle is caused by the changing relative velocities of the Earth and the ISM responsible for the scattering [17]. If the ISM velocities follow the local standard of rest, LSR, many sources would be expected to show a slowing down in the third quarter of the year, and hence may more easily be missed because of the lengthened time scales. If the scattering material responsible for the scintillation follows the LSR, then we would expect many more sources to exhibit their slow-down during the September session. Figure 3 shows the numbers of variables found at each of the four epochs. A contingency test shows no evidence that the numbers differ from the mean in any epoch, even though epoch 3 lasted for 4 days rather than 3 days. The uniformity of variable numbers in each epoch shows no evidence for a September slow-down; it appears that the majority of the scattering material is not moving at the LSR. This is perhaps not unexpected; both PKS 1257–326 and J1819+3845, two sources for which reliable screen velocities have been measured, have measured screen velocities that differ significantly from the LSR [2,15].

## 7. Galactic latitude dependence

We asked the question 'are the latitude distributions of variables and non-variables the same?' A contingency test dividing them into a low-latitude sample, $|b| < 40°$, and a high latitude sample, $|b| > 40°$, shows that, at the 98% confidence level, the two distributions differ significantly. There are fractionally more variables at low latitudes than that at high latitudes, so providing unambiguous support for the origin of the IDV being ISS. This is in excellent agreement with the modulation index dependence found by Rickett *et al.* [18] in their analysis of the 146 flat-spectrum sources observed with the Green Bank Interferometer.

## 8. Spectral index dependence

The MASIV sources were selected to have spectral indices greater than −0.3 [3]. We have searched for a spectral index dependence by dividing the sources into two approximately equal groups at a spectral index of 0.1 and by testing whether these fraction of scintillators in these two groups are the same or not. The contingency test tells us immediately that the probability is less than 1% and that these two groups were drawn from the same population.

The spectral index distribution for sources surveyed at 5 GHz is bi-modal with peaks near 0 and −0.7. These two peaks result from two distinct source populations; the steep spectrum sources are predominantly nearby galaxies, while the flat-spectrum sources are predominantly distant quasars [19]. However, the spectral index distribution of galaxies contains a significant number with spectral indices flatter than −0.3, and it is these that are likely responsible for the spectral index dependence noted here.

## 9. Redshift dependence

We have extracted redshifts from the literature for 154 of the MASIV variables and non-variables. We have measured redshifts for a further 39 sources in a pilot programme with the 2.5 m Nordic Optical Telescope (Pursimo *et al.* in preparation) and the overall redshift distribution is given in figure 4. A contingency test on the data in figure 4 reveals that the redshift distributions of the scintillators and non-scintillators are clearly different at the 97% confidence level, in the sense that there is a deficit of scintillators among the high redshift sources.

We can test this distinction further by dividing the sources into two separate groups: 'near universe', namely those with $z < 2$, and 'far universe', those with $z > 2$. Such a division is appropriate on astrophysical and especially on observational grounds; those sources with redshifts of ≥2 show the presence and pattern of the usual strong quasar emission lines [Lyman Alpha, Si IV, CIV and CIII], as well as the presence of the Lyman Alpha absorption forest, which is easily recognizable in establishing a redshift of ≥2. Such a test with a division at $z = 2$ is extremely robust as the spectra of $z \geq 2$ quasars are easily and unambiguously recognizable, and avoids the need for accurate redshifts. BL Lacs are also easily included as the absence of any Lyman Alpha forest absorption classifies them as $z < 2$ as well.

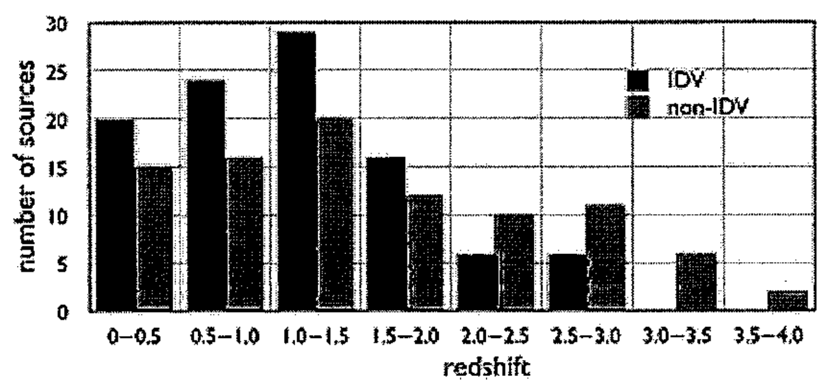


Figure 4. The redshift distributions of the scintillators and non-scintillators. We detect a significant deficit of scintillators at redshifts >2, which may be a signature of scattering in the turbulent ionized intergalactic medium.

The use of only two redshift categories maximises the numbers and provides a powerful statistical test which yields a formal probability of <0.1% that the low and high universe groups are drawn from the same population. There is a highly significant deficit of scintillators in the far universe.

However, we are concerned regarding the possibility that selection effects present in the redshifts from the literature, which constitute three quarters of the measured redshifts, may masquerade as a redshift dependence. For example, more redshifts exist in the literature for the stronger sources, so differences between the stronger and weaker sources may show as a redshift dependence. It is for this reason that it is essential that we complete the redshift measurements for all of the MASIV sources and that this be achieved expeditiously.

It seems unlikely that radio sources are intrinsically larger at high redshift. We interpret the deficit of high redshift scintillators as due to intergalactic scattering where ISS acts as a filter to distinguish sources containing apparent microarcsecond components from those that do not. The absence of IDV in sources above $z \sim 2$ indicates they are too large to scintillate. This implies that sources at $z > 2$ are either (a) intrinsically too large to scintillate or (b) are being scatter-broadened by turbulence in the ionized intergalactic medium at redshifts in excess of 2.

## 10. Conclusions

- A total of 56% of sources varied on one or more of the four observing epochs.
- We found a significant Galactic latitude dependence with fewer variables at high Galactic latitudes. This strongly supports ISS as the mechanism responsible for the observed variability.
- Rapid, high modulation, interhour variable sources are rare.
- Number of variables in each epoch does not follow what is expected for LSR screens.
- We found a significant spectral index dependence, with fewer scintillators with smaller spectral indices.
- Variability time scales are slow, ~1 day or more; there are approximately ten 'fast' sources (three or more inflections)
- We found few scintillators at redshifts of $\geq$2. We argue that this is caused by scattering in the turbulent IGM.

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